

## FINAL REPORT

**Subject** Development of near-field-light lens for nano-focusing of atoms

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**Abstract** We made a near-field optical lens to focus Rb atoms on a nanometer spot by nanofabrication of a silicon-on-insulator wafer. The intensity distribution of near-field light used for atom concentration was obtained from the finite difference time domain simulations. The atomic motion falling through the lens was examined by solving the Schrödinger equation. In addition, we fabricated a nano-slit to detect the focused atoms and numerically estimated the detection efficiency of Rb atoms.

### 1. Goal

Nanometer-sized optical devices based on near-field optical interactions, including optical switches and logic gates, have been proposed. The nanophotonic devices consist of several quantum dots properly size-controlled. Moreover, the quantum dots must be properly arranged left a nanometer space one another for signal transmission. Toward fabrication of the nanostructure, we develop an atom-focusing system using local selective interaction with nanometric near-field light.

### 2. Principle

Figure 1 schematically shows atom focusing with the near-field-light lens (paper [1]). Near-field light is produced near inner edge of the small hole by coupling far-field light. The radius of curvature of the edge is below 100 nm and the other part is coated with Au metal. When the light frequency is slightly higher than the atomic resonant frequency (blue detuning), the repulsive dipole force acts on atoms. As a result, atoms entering the near-field-light region are concentrated into a nanometer-scale spot.

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14. ABSTRACT <b>The researchers made a near-field optical lens to focus Rb atoms on a nanometer spot by nanofabrication of a silicon-on-insulator wafer. They also fabricated a nano-slit to detect the focused atoms and numerically estimated the detection efficiency of Rb atoms.</b>				
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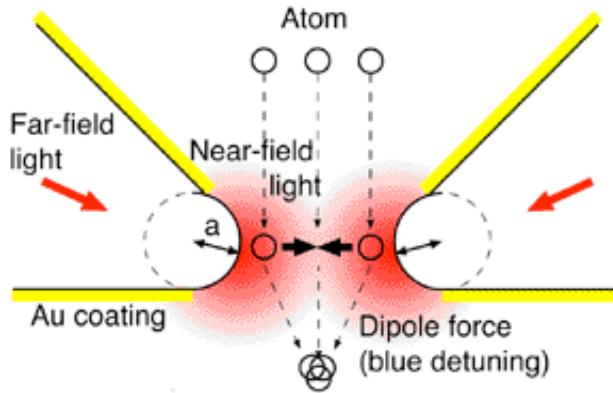


Fig. 1 Focusing atoms with repulsive dipole forces from blue-detuned near-field light.

### 3. Fabrication

We made a device used as the atom lens by processing a silicon-on-insulator (SOI) wafer composed of five layers: a 3- $\mu\text{m}$ -thick  $\text{SiO}_2$  layer is sandwiched by a 40- $\mu\text{m}$ -thick and a 300- $\mu\text{m}$ -thick Si layer, and the both surfaces are coated by 2- $\mu\text{m}$ -thick  $\text{SiO}_2$  layers. Figure 2 shows the fabrication process. First, (a) we removed the center part of the film oxide on the lower side by photolithography, and (b) made legs to support the lens part by anisotropic chemical etching with 22-wt% KOH for two hours and 22-wt% TMAH for four hours at 80 °C. Then, (c) we removed the film oxide on the upper side by photolithography, leaving a small part, and (d) made a hollow inverse pyramidal structure by anisotropic chemical etching with 27-wt% KOH and 16-% IPA for 52 minutes at 80 °C. Moreover, (e) we removed the residual  $\text{SiO}_2$  film with BHF for a half hour. Finally, (f) we conducted 78-nm-thick Au coating by vacuum evaporation.

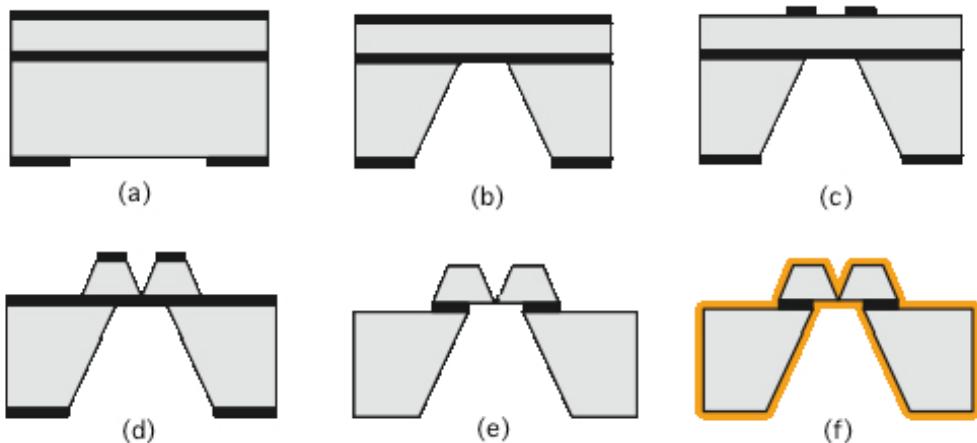


Fig. 2 Fabrication process.

Figure 3 shows the SEM image. The center part works as the atom lens. Near-field light is generated near the exit hole produced at the bottom of the hollow inverse pyramidal structure by illuminating the four sides with laser beams guided through optical fibers.

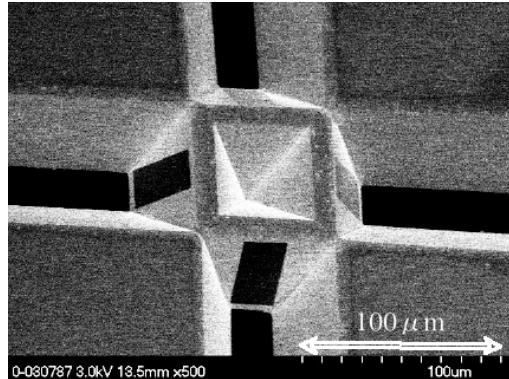


Fig. 3 SEM image of the hollow inverse pyramidal structure used for focusing

The shape of the exit hole is usually rectangular as shown in Fig. 4(a). For homogeneous focusing, we made it circular as shown in Fig. 4(b) by etching with HF:HNO<sub>3</sub>:CH<sub>3</sub>COOH = 1:5:2 for 1 sec at 22 °C under the rate of 7.4 μm/min. In this case, the hole-diameter was 500 nm and the radius of curvature was estimated to be 45±5 nm. The localized length of near-field light is expected to be comparable to the radius of curvature.

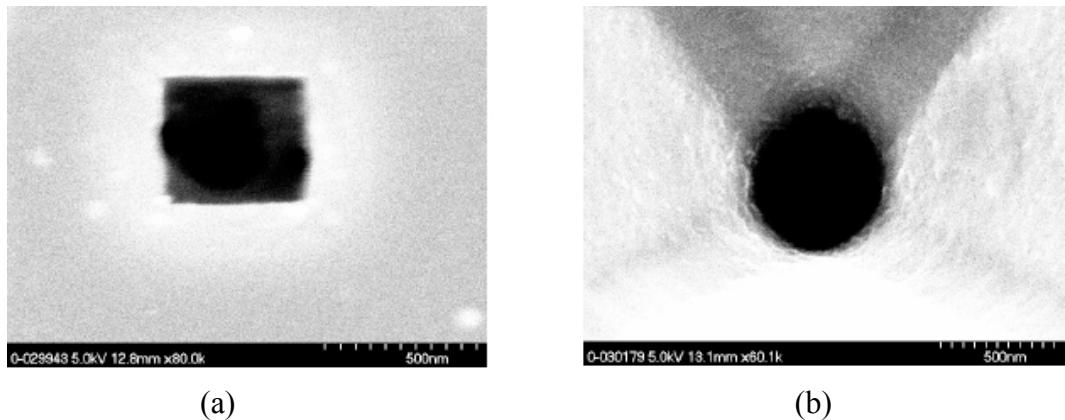


Fig. 4 SEM images of the outlet. (a) rectangular case, and (b) circular case.

#### 4. Simulations

In order to examine the feasibility of nanofocusing, we conducted a couple of simulations. Figure 5 shows the light intensity distribution in the 500-nm-hole at the bottom of the hollow inverse pyramidal structure in the case of the wavelength of 780 nm used for Rb atom

manipulation. The 2D map is drawn based on the finite difference time domain (FDTD) analysis with *Poynting* (Fujitsu, purchase software). The decay length from the inner edge of the hole strongly depends on the incident light polarization. For the s-polarization parallel to the light incident wall of the fabricated device, the near-field light intensity decreases down to  $10^{-3}$  at the center. In this case, the throughput that is defined as the ratio of the near-field-light intensity to the incident far-field-light one is estimated to be 0.24 for the aperture length (the uncoated part of the inner edge) of 27 nm. The value is sufficient for deflecting Rb atoms going through the hole by repulsive dipole forces from blue detuned near-field light.

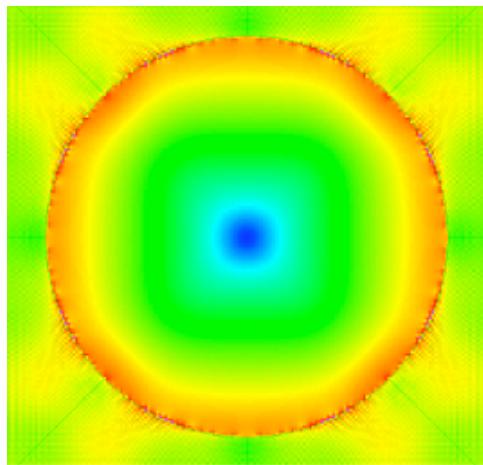


Fig. 5 Intensity distribution of near-field light induced around the circular outlet.

Then, we numerically examined the atomic behavior by solving the Schrödinger equation for the corresponding Gaussian wave packet. Figure 6 shows trajectories of Rb atoms vertically outputted from the 500-nm-wide hole. We assume that cold Rb atoms are generated by a magneto-optical trap, which is the standard technique of laser cooling of neutral atoms, above the near-field-light lens and the incident velocity is 1 m/s. The focal length is calculated to be 56 nm.

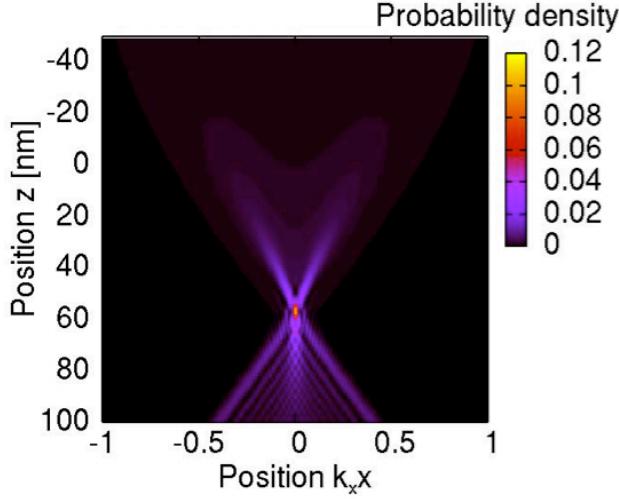


Fig. 6 Numerical calculation of focusing cold Rb atoms.

Figure 7 shows the spatial profile of Rb atoms at the focal point. The FWHM of the 0<sup>th</sup> diffraction pattern of the de Broglie wave is estimated to be 2 nm, which is comparable to the de Broglie wavelength..

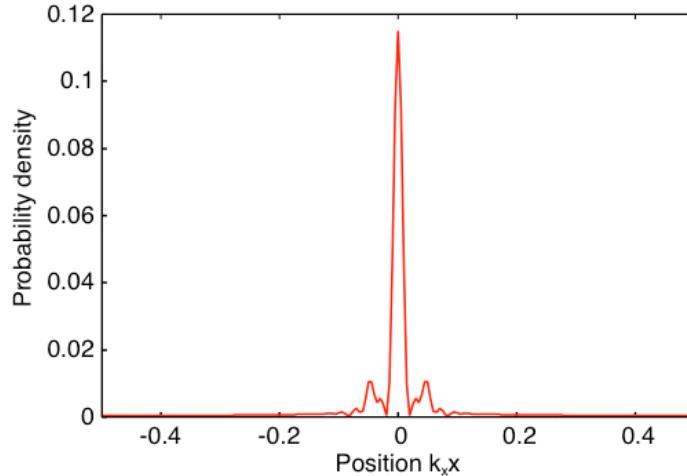


Fig. 7 Spatial profile of the focused Rb atoms numerically obtained.

## 5. Atom detector

The demonstration experiments require high sensitive and high spatial resolution detection of a small number of atoms. To this end, we plan to use a nano-slit as shown in Fig. 8. In this scheme, atoms are ionized by two-step photoionization with two-color near-field lights generated via total-internal reflection and counted with an ion detector such as channel electron multiplier. For example, <sup>87</sup>Rb atoms in the 5S<sub>1/2</sub>, F=2 ground state are excited to the 5P<sub>3/2</sub>, F=3 state by 780-nm light and then ionized by 476.5-nm light. From the two-step photoionization experiments with two-color evanescent lights, we estimated that the

ionization cross section from the 5P state was  $2.0 \times 10^{-17} \text{ cm}^2$  (paper [2]).

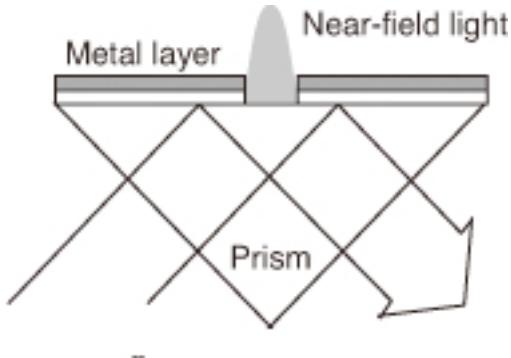


Fig. 8 Side view of the slit-type atom detector using two-color near-field lights

We fabricated a 50-nm-wide slit on a glass substrate using the lift-off process with a bilayer resist including Cr. Conducting the FDTD simulations, we drew the spatial profiles of near-field lights generated in the vicinity of the slit. In the slit-parallel-incident configuration with s-polarization, we obtained a good throughput of  $1.1 \times 10^{-2}$ . In this case, the ionization efficiency of low-energy  $^{87}\text{Rb}$  atoms in the  $5\text{S}_{1/2}$  hyperfine state is estimated to exceed 1 % (paper [3]).

## 6. Summary

The SOI fabrication is useful for making of near-field optical devices, including atom lens and detector, with specific structure below 100 nm. Blue-detuned near-field light generated in a small hole works as a sort of lens that focuses atoms on a sub-10-nm spot. On the other hand, blue-detuned near-field light generated on a nano-slit can be applied to high-spatial resolution detection of neutral atoms.

## Original Papers

- [1] H. Ito, K. Yamamoto, A. Takamizawa, H. Kashiwagi, T. Yatsui: “Deflecting, focusing, and funneling atoms by near-field light,” *J. Opt. A: Pure Appl. Opt.* Vol. 8, S153-S160 (2006).
- [2] K. Yamamoto, K. Totsuka, H. Ito: “Two-step photoionization of cold atoms by two-color evanescent-light waves and application to atom detection with high spatial resolution,” *Opt. Commun.* Vol. 265, 692-695 (2006).
- [3] T. Sato, H. Ito: “Sub-100-nm-wide slit for detecting ground state atoms with near-field photoionization,” *J. Nanophoton.* Vol. 1, 011560 (2007).

## **International Conference**

- [1] T. Sato, K. Yamamoto, H. Ito, "Generation of near-field light on a sub-100-nm-wide slit by illumination via total-internal reflection and application to atom detection with high spatial resolution," 9<sup>th</sup> international Conference on Near-field Optics, Nanophotonics & Related Techniques, Lausanne, September, 2006.
- [2] H. Ito, K. Yamamoto, T. Sato, "Deflecting, focusing, and detecting atoms using near-field light (invited)," Nanometa 2007, Seefeld, January, 2007.
- [3] T. Sato, M. Sato, H. Ito, "Near-field light lens for nano-focusing of atoms," 6<sup>th</sup> Asia-Pacific Conference on Near-Field Optics, Huangshan, June, 2007.